Space Suit CO_2 Washout During Intravehicular Activity

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Nomenclature

acfm	actual cubic feet per minute
Btu	British thermal units
CDC	Center for Disease Control
CFD	computational fluid dynamics
cfm	cubic feet per minute
CO_2	carbon dioxide
CSSE	Constellation Space Suit Element
CTSD	Crew and Thermal Systems Division – JSC
CxP	Constellation Program
EVA	extravehicular activity
ECLSS	Environmental Controls and Life Support System
EDAC	EVA Design Analysis Cycle
EMU	extravehicular mobility unit
ESPO	EVA Systems Project Office
H_2O	water
hr	hour(s)
HSIR	Human-Systems Integration Requirements
in.	inch(es)
IRMA	Integrated Risk Management Application
IVA	intravehicular activity
JSC	Johnson Space Center
LEA	launch, entry, abort
mmHg	millimeters of mercury
NIOSH	National Institute of Occupational Safety and Health
O_2	oxygen
OSHA	Occupational Safety and Health Administration
p/f	pass/fail
PGS	Pressure Garment Subsystem
psia	pounds per square inch absolute
SE&I	Systems Engineering and Integration
SME	subject matter expert

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I. Abstract

Space suit carbon dioxide (CO_2) washout refers to the removal of CO_2 gas from the oral-nasal area of a suited astronaut's ("crewmember's") helmet using the suit's ventilation system. Inadequate washout of CO_2 can result in diminished mental/cognitive abilities as well as headaches and lightheadedness. In addition to general discomfort, these ailments can impair an astronaut's ability to perform mission-critical tasks ranging from flying the space vehicle to performing lunar extravehicular activities (EVAs).

During design development for NASA's Constellation Program (CxP), conflicting requirements arose between the volume of air flow that the new manned space vehicle is allocated to provide to the suited crewmember and the amount of air required to achieve CO_2 washout in a space suit. Historically, space suits receive 6.0 actual cubic feet per minute (acfm) of air flow, which has adequately washed out CO_2 for EVAs. For CxP, the vehicle will provide 4.5 acfm of air flow to the suit. A group of subject matter experts (SMEs) among the EVA Systems community came to an early consensus that 4.5 acfm may be acceptable for low metabolic rate activities. However, this value appears very risky for high metabolic rates, hence the need for further analysis and testing.

A thermal analysis was performed to validate the 4.5 acfm value and to determine if adequate CO_2 washout can be achieved with the new suit helmet design concepts. The analysis included computational fluid dynamic (CFD) modeling cases, which modeled the air flow and breathing characteristics of a human wearing a suit helmet. Helmet testing was performed at the National Institute of Occupational Safety and Health (NIOSH) in Pittsburgh, Pennsylvania, to provide a gross-level validation of the CFD models. Although there was not a direct data correlation between the helmet testing and the CFD modeling, the testing data showed trends that are very similar to the CFD modeling. Overall, the analysis yielded results that were better than anticipated, with a few unexpected findings that could not easily be explained. Results indicate that although 4.5 acfm of suit inlet airflow can provide adequate CO_2 washout for suited intravehicular activities (IVAs), it is highly dependent upon helmet geometry and ventilation routing. This paper summarizes the results of this CO_2 washout study.

II. Purpose

The purpose of this paper is to document a study that characterized CO_2 washout performance of space suit helmets. The objective of this study was to validate an air flow rate of 4.5 acfm from the space vehicle's life support suit ventilation loop as acceptable to provide adequate CO_2 washout to the crew during suited IVAs. CFD modeling and suit helmet testing were performed in order to validate the flow rate. Based on the data acquired, this paper indicates that a suit helmet can accept the 4.5 acfm flow rate from the suit loop to provide CO_2 washout.

III. Background

Adequate removal of CO_2 from within the suit depends largely on helmet design and volumetric air flow of the breathing gas coming into the suit via the helmet. Historically, the EVA community has been comfortable with 6.0 acfm of air flow and subsequently designed helmets to work with that flow rate. Under CxP direction, the vehicle is being designed with a suit ventilation loop that will provide 4.5 acfm of breathing air to the suit. Many within the program believed that this would be sufficient since the application is for low metabolic rate IVA-type operations such as flying the vehicle or reconfiguring the cabin throughout the different mission phases in both a pressurized and unpressurized cabin. Designing a suit loop that can support the proven 6.0 acfm of breathing air incurs an increase in mass and power consumption that are outside of the current design parameters for the vehicle.

Conversely, NASA has never built a continuous flow space suit helmet to operate at 4.5 acfm, and at the beginning of this study, there was concern that adequate CO_2 washout could not be attained with this flow rate. For launch, entry, and abort (LEA) scenarios, a demand system has been used in helmets to provide washout, but direct comparisons between continuous flow and demand systems are difficult to evaluate. The CO_2 washout study was initiated in January 2009 to assess at a high level the feasibility of using the 4.5 acfm flow rate with helmets that represent the current Constellation Space Suit Element (CSSE) reference architecture.

III. Assumptions

The following assumptions were used throughout this analysis:

Assume 4.5 acfm [acfm for CFD models and cubic feet per minute (cfm) for NIOSH test cases] of air flowing into the helmet and measured at the air flow source.

Assume LEA scenarios where the crew will see 14.7 pounds per square inch absolute (psia) of ambient air pressure within the cabin plus approximately 0.5 psia vent pressure within the suit.

Assume an unpressurized cabin survival scenario in which the suit will be pressurized to 4.3 psia.

Assume metabolic rates of 800 British thermal units per hour (Btu/hr) to represent the crewmembers in a resting state during launch and reentry, as well as 1600 Btu/hr to represent crewmembers under high stress during an abort or other contingency scenario.

Assume continuous flow helmets for all CFD and NIOSH test cases. Demand breathing systems were not evaluated during this study.

Assume air outlet boundary conditions to be located around the neck region.

IV. Technical Approach

Two phases of the study occurred from January to October 2009. For phase one, the analysis team consisted of the lead analyst and thermal analysts who solicited subject matter expertise to perform a subjective evaluation of the CO_2 washout issue. Phase two called for the analysis team to quantify the phase one conclusions using CFD analysis and hardware testing.

A. Phase One: Subjective Consensus

Phase one consisted of discussion sessions with EVA SMEs to discuss the feasibility of using an air flow rate of 4.5 acfm to provide adequate CO_2 washout in a space suit. Representatives within the EVA community -- the EVA Systems Project Office (ESPO) chief engineer, Pressure Garment Subsystem (PGS) SMEs, and thermal analysis SMEs -- as well as representatives from the space medicine community participated in this discussion. The basic conclusions were as follows:

- 4.5 acfm might be acceptable for CO_2 washout during low metabolic rate activities.
- 4.5 acfm is a risk during high metabolic rate activities such as the LEA phases of a flight.

Regardless of the flow rate, helmet design is a significant factor to providing proper CO_2 washout.

Phase one ended with the decision to continue this analysis as phase two follow-on task by quantifying the conclusions drawn thus far.

B. Phase Two: Quantifying CO_2 Washout

Phase two of this study characterized CO_2 washout performance using the three helmet configurations previously discussed. The thermal analysis consisted of CFD modeling to run the LEA and unpressurized cabin scenarios. Shortly thereafter, helmet testing with a mechanical breathing apparatus provided both a set of data points to characterize performance as well as a means of validating the CFD models.

Test and analysis runs were considered successful by the analysis team if the average partial pressure of CO_2 that was breathed in by the human measured less than 7.6 millimeters of mercury (mmHg). This value was derived from legacy Extravehicular Mobility Unit (EMU) suit requirements and *CxP 70024, Constellation Program Human Systems Integration Requirements* (referred to herein as “HSIR”). The space medicine community at Johnson Space Center (JSC) disagreed with the analysis team regarding the interpretation of the CO_2 washout requirement, maintaining that the success criterion should be less than 5.0 mmHg instead of 7.6 mmHg. The analysis team did not resolve this discrepancy during the study and carried both success criteria as part of the results which will be referred to as the space medicine success criterion (5.0 mmHg) and EVA success criterion (7.6 mmHg).

Three different space suit helmets will be used for the CFD and the NIOSH testing that are derived from the CxP EVA technical baseline. This includes the following:

- A hemispherical conformal helmet that isolates the volume immediately in front of the face for air flow and CO_2 washout.
- A face dam conformal helmet – A variant of a military helmet that is currently in service and also incorporates the isolated face-volume concept.
- A hemispherical helmet in an open configuration – This provides a basis of comparison for CO_2 washout data. Comparing this data against the conformal helmet provides a good look at the common helmet concept that is part of the technical baseline.

Once the team completed testing with these helmets, alternative configurations of the hemispherical helmet were tested using different combinations of the conformal foam, a foam neck dam, and the new air duct that was developed for the testing. The intent of this testing was to characterize how those features affect CO_2 washout performance. Additionally, test data from a Gentex® mine rescue helmet was utilized for comparison purposes against the suit helmets.

1. CFD Modeling

The CFD cases began with the most conservative parameters while holding the air flow as a constant at 4.5 acfm. The inlet air flow assumed 2.3 mmHg partial pressure of CO_2 injected into the line to represent the maximum nominal CO_2 that will flow into the helmet from the suit loop. The metabolic rate was set at 1600 Btu/hr, which represents the metabolic rate of the crewmember when dealing with launch loads and vibration, as well as a high-stress contingency scenario. As the analysis progressed, metabolic rates and ambient air pressure parameters were changed to acquire more data points to characterize helmet air flow.

The analysis team ran cases at 3.0, 5.0, and 6.0 acfm to characterize alternative flow rates to the 4.5-acfm value that was established. The value of 3.0 acfm represents a target flow rate the vehicle may be able to provide in the suit loop and still meet mass and power constraints. Values of 5.0 and 6.0 acfm represent possible flow rate options if the 4.5 acfm value is deemed inadequate. All of the runs maintained 2.3 mmHg of CO_2 injected into the helmet.

Hemispherical Conformal Helmet

The hemispherical conformal helmet represents the helmet concept that is closest to the CxP EVA reference architecture. It combines the hemispherical helmet with occupant protection inserts that function as a face dam, and a multi-hole spray bar that blows air into the helmet similar to the face dam conformal helmet. This face dam concept partitions the volume of space in front of the face from the rest of the head as the air flow volume of interest for breathing and suit air flow. Air flows into the helmet from 16 inlet holes in a spray bar across the top of the helmet (above the eyes), and out of the helmet through an outlet port that is 3 inches (in.) long and 1/2-in. wide (in front of the chin). See Fig. 1 and Fig. 2.

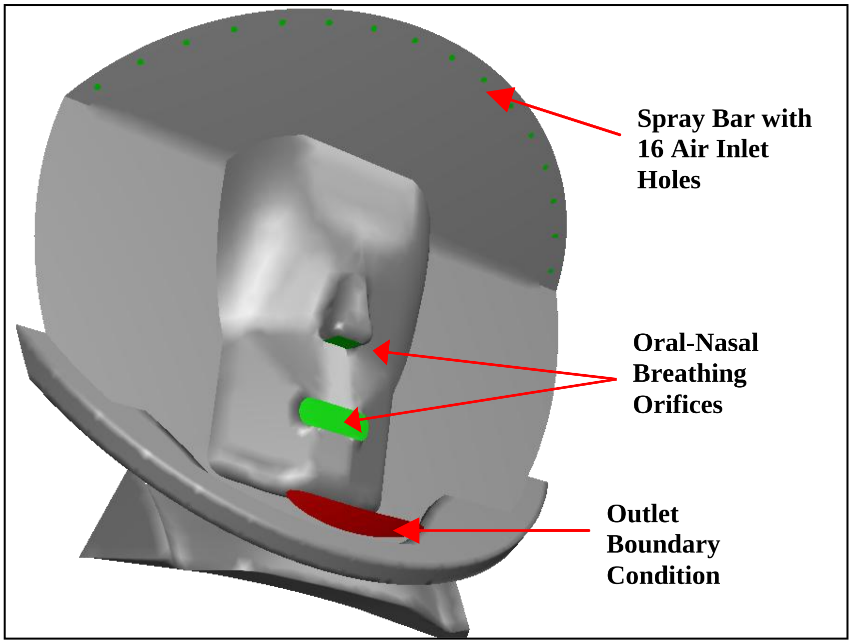


Figure 1. Boundary conditions of the hemispherical conformal helmet.

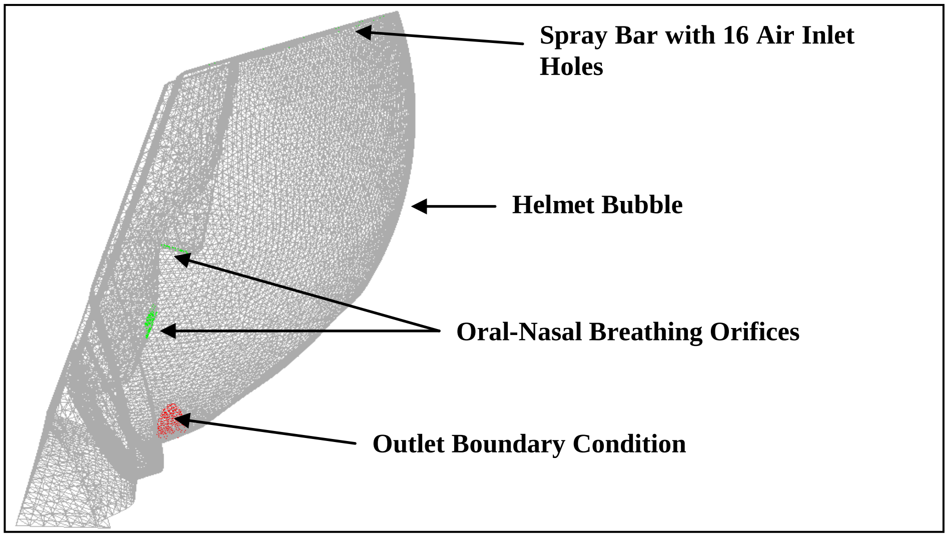


Figure 2. Profile of hemispherical conformal helmet.

Hemispherical Open Helmet

The hemispherical open helmet represents an open-helmet configuration that includes air volume around the head and neck as the air flow volume of interest. See Fig. 3. Air flows into the helmet from a rectangular-shaped inlet just above the head that measures 4 in. by 1/2 in., and flows in front of the face, through the neck region, and out through the upper torso of the suited crewmember. See Fig. 4. This model is a pre-existing model with air outlet boundary conditions at the bottom of the upper torso and at the end of the arms; however, for this study, it is assumed to have same outlet flow characteristics as the neck-area boundary conditions of the other test cases.

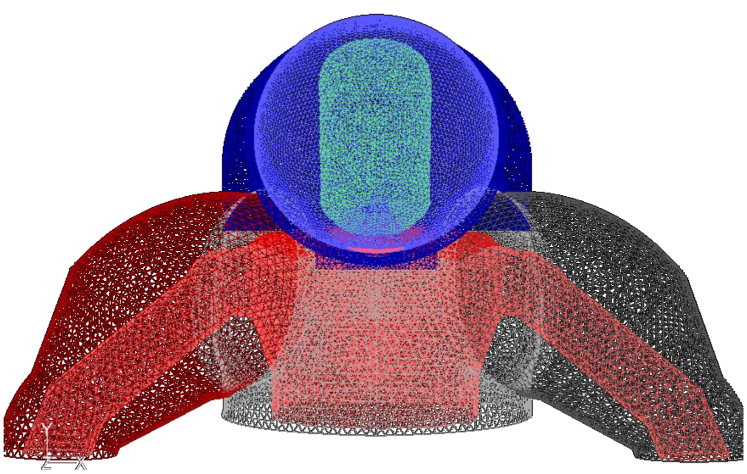


Figure 3. Front view of hemispherical open helmet model.

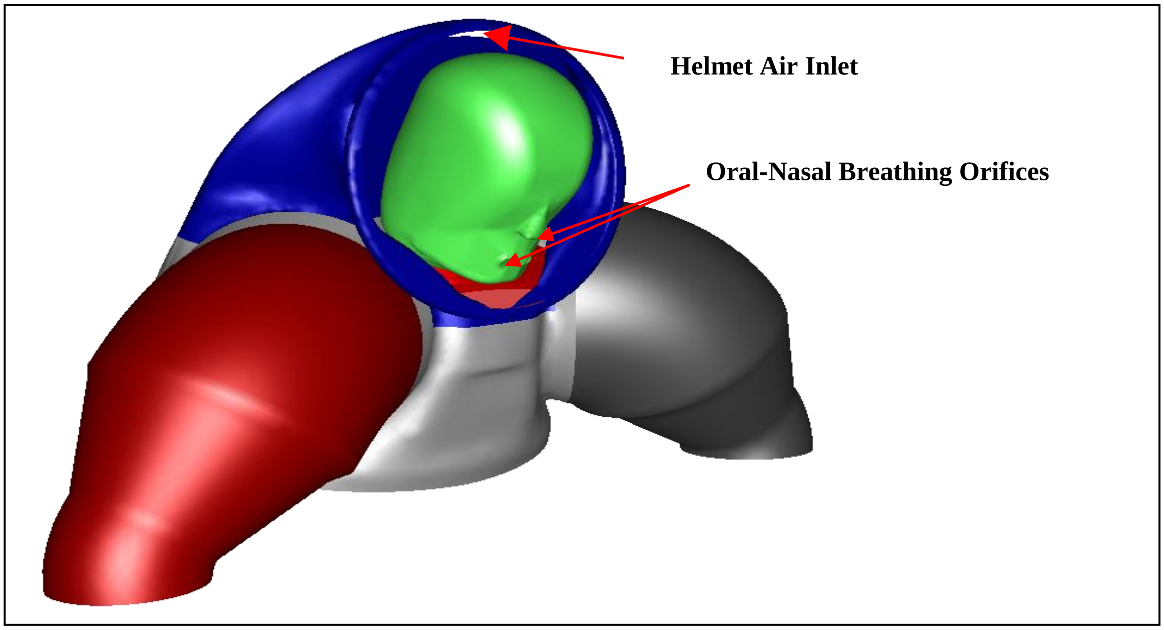


Figure 4. Oblique view of hemispherical open helmet model.

Face Dam Conformal Helmet

The face dam conformal helmet represents an isolated facial volume helmet that is currently in military service. See Fig. 5. The actual helmet operates as a demand breathing system with a demand regulator and a check valve at the breathing outlet that allows the flow of air in and out of the helmet each time the crewmember takes a breath. The model functions as a continuous air flow helmet, which is consistent with the reference suit architecture. Air flows into the helmet through inlet air holes located along the perimeter of the helmet-visor interface and flows out of a single round opening near the chin of the head form. See Fig. 6.

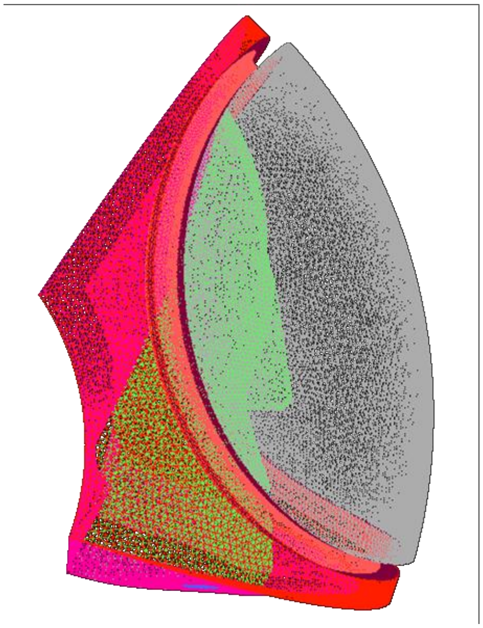


Figure 5. Side view of face dam conformal helmet model.

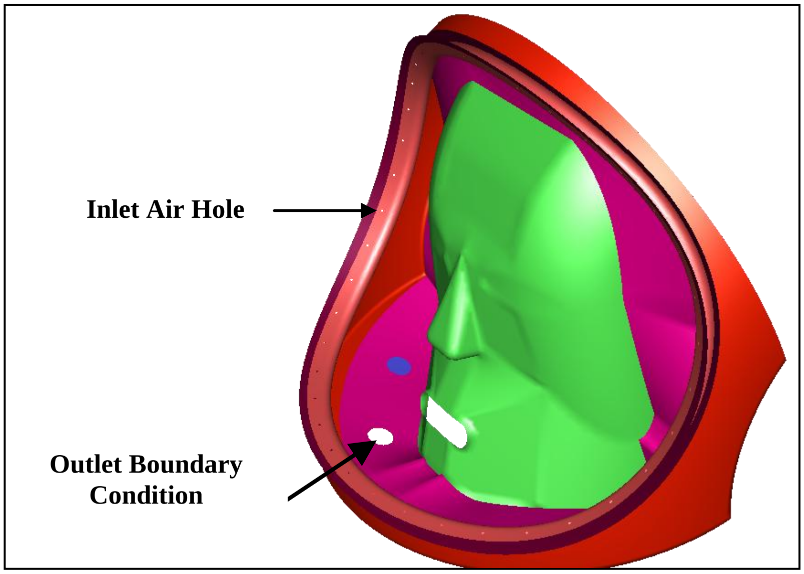


Figure 6. Inlet and outlet of face dam conformal helmet model.

CFD Results

The analysis team expected the low-volume helmet concepts (i.e., the face dam conformal helmet and the hemispherical conformal helmet) to meet or exceed the EVA success criterion. The rationale was that a smaller volume of air would allow for less mixing to occur between fresh air and CO_2, and allow a more concentrated flow of CO_2 out of the helmet. In reality, the CFD modeling showed no consistent trends between the low-volume helmets and the higher-volume hemispherical open configuration helmet. See Table 1.

The 3.0 acfm cases generally performed well against the EVA success criteria, but not as well against the space medicine limit. The hemispherical conformal helmet that most closely represented the Cx EVA reference architecture helmet failed the highest risk case - the high-metabolic rate launch/entry case - based on both success criteria. The hemispherical open configuration helmet performed generally well against the EVA success criterion at 3.0 acfm, but the face dam conformal helmet did not. Given the variability of the 3.0 acfm analysis results and the difference in success criteria, the analysis team does not recommend an inlet flow rate of 3.0 acfm.

At 4.5 acfm, the hemispherical open configuration helmet consistently performed better than the hemispherical conformal helmet. Both helmets exhibited diminished performance at high metabolic rates of 1600 Btu/hr, as expected. The hemispherical conformal helmet failed both the EVA and the Space Medicine success criteria during the high-metabolic launch/entry case and almost failed both criteria during the high-metabolic unpressurized cabin scenario. The hemispherical open configuration helmet passed the EVA success criterion for the high-metabolic case and then passed both success criteria for the high-metabolic unpressurized cabin scenario. Both helmet configurations performed fairly well at 4.5 acfm during the low-metabolic rate cases. The face dam conformal helmet performed similarly to the hemispherical open configuration helmet. It passed the EVA success criterion for the high-metabolic rate launch/entry cases at 4.5 acfm.

The 5.0 and 6.0 acfm models yielded some unexpected mixed results that could not be readily explained. For the high-metabolic rate cases, the CO_2 washout predictably improved as the suit loop flow rate increased. The face dam helmet passed both success criteria for the low-metabolic launch/entry cases at 5.0 and 6.0 acfm. However, for the high metabolic rate launch/entry cases using the hemispherical open configuration, the CO_2 washout actually worsened as the flow rate increased. This result is also seen in some of the helmet testing performed at the NIOSH, and in both cases, the analysis team was not able to explain this occurrence. Without an explanation for this, the team did not have enough data to distinguish improvements in CO_2 washout performance from 4.5 and 6.0 acfm.

The analysis results emphasized the importance of a proper helmet design to attain adequate CO_2 washout. The low-volume helmet concepts did not perform consistently well, but the hemispherical open configuration helmet performed better than the low-volume helmets. Overall, 4.5 acfm proved to be an attainable flow rate to properly washout CO_2. Thus, based on the CFD models, the team recommends accepting 4.5 acfm for a vehicle suit loop flow rate.

Table 1. CFD analysis results.

Model	Hemispherical Conformal Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
Met Rate (BTU/hr)	800				1600				800				1600			
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	6.9	5.2	4.8	4.2	11.6	8.2	7.4	6.2	4.8	4.6	4.4	3.9	7.5	7.3	6.8	5.8

Model	Hemispherical Open Configuration Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
Met Rate (BTU/hr)	800				1600				800				1600			
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	4.5	3.8	3.9	4.3	6.7	5.3	5.5	6.2	3.6	3.3	3.3	3.3	5.3	4.6	4.4	4.3

Model	Face Dam Conformal Helmet															
	Launch/Entry (15.2 psi)								Unpress 1 (4.3 psi)				Unpress 2 (4.3 psi)			
Met Rate (BTU/hr)	800				1600				800				1600			
Volumetric Flow Rate (acfm)	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6	3	4.5	5	6
Avg CO2 Inhaled (mmHg) (velocity weighted)	5.6	3.7	3.4	2.8	9.1	5.3	4.6	3.4	5.4	3.2	3.3	2.9	9.2	4.5	4.2	3.2

	Test point passes both the Space Medicine and EVA pass/fail (p/f) criteria of 5.0 mmHg and 7.6 mmHg average inhaled $ppCO_2$.
	Test point fails the Space Medicine p/f criterion of 5.0 mmHg average inhaled $ppCO_2$, but passes the EVA p/f criterion of 7.6 mmHg.
	Test point fails both the Space Medicine and EVA p/f criteria of 5.0 mmHg and 7.6 mmHg average inhaled $ppCO_2$.

2. Helmet Testing at the NIOSH

As a means of validating the CFD data, the analysis team performed testing to characterize CO_2 washout performance using helmets that are similar in configuration to the CFD models. NIOSH offered a metabolic breathing instrument in Pittsburgh, Pennsylvania to perform this testing. The test data indicated many of the same trends that the CFD modeling showed, providing a gross-level validation of the CFD models. The analysis team performed additional tests on variations of the hemispherical helmet configurations to characterize the performance of different helmet features.

The helmet testing incorporated the same test parameters used during the CFD work. The team ran the inlet air flow at 3.0, 4.5, and 6.0 cfm assuming both low- and high-metabolic rates of 800 and 1600 Btu/hr. Some test cases included CO_2 injected into the inlet at a partial pressure of 2.3 mmHg to represent the maximum allowable CO_2 into the suit vent loop.

NIOSH Overview

NIOSH is a federal agency under the Centers for Disease Control (CDC) whose objective is to research and provide recommendations for preventing workplace injuries and illnesses. This differs from the Occupational Safety and Health Administration (OSHA) because OSHA is a Department of Labor agency that is responsible for enforcing workplace safety regulations and practices. The NIOSH facility in Pittsburgh focuses primarily on requirements and standards for mine and fire rescue helmets and their corresponding breathing apparatuses.

The test stand used to test the mine and fire rescue hardware consists of an artificial lung that breathes through an attached head form for helmet interface. See Fig. 7 and Fig. 8. Metabolism of the test stand can be adjusted to reflect the respiration rates, humidity, and air temperature associated with human breathing characteristics at that set metabolic rate. The test stand can also be configured to measure the amount of CO_2 inspired with a helmet donned, which is the key feature the analysis needed to test the suit helmets. The inlet flow rate of air can be adjusted to within 0.1 cfm, flowing both clean ambient air as well as air injected with a supply of CO_2 to represent the maximum amount of CO_2 that the ECLSS suit loop can flow into the suit.

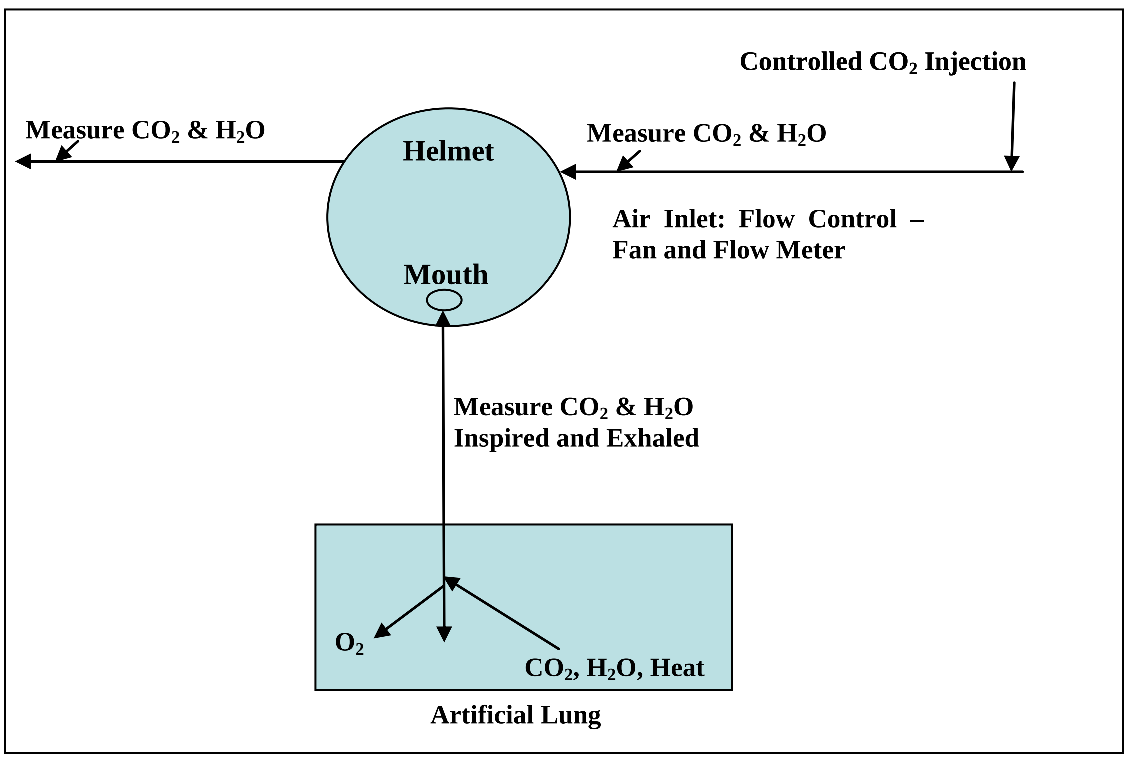


Figure 7. Schematic diagram of NIOSH test stand.

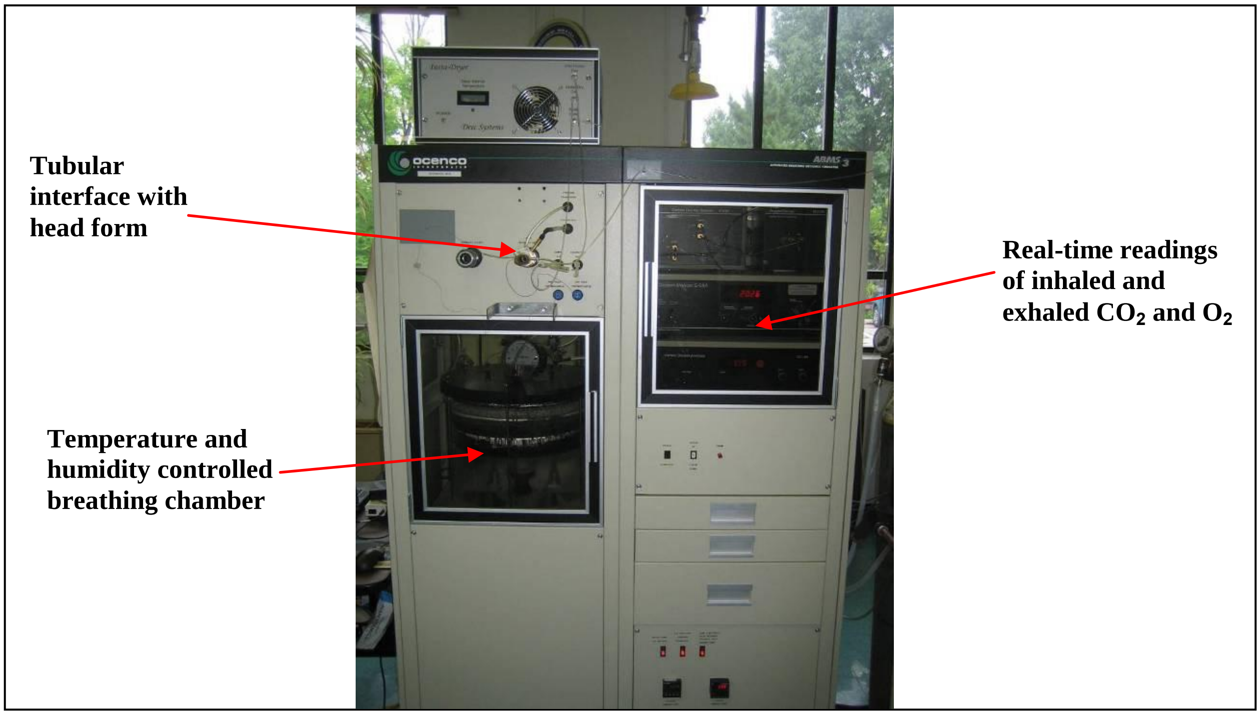


Figure 8. Actual NIOSH test stand.

Suit Helmet Test Articles

The analysis team used the hemispherical helmet dome along with a neck wedge to build up both the hemispherical conformal helmet and the hemispherical open configuration helmet. The hemispherical open helmet was placed on the head form with a piece of sheet metal curled at the ends in order to suspend the helmet above the head form to simulate the actual position of the helmet on a suited crewmember. See Fig. 9. A metal fitting was used as an interface between the air supply line and the neck wedge. The back part of the neck wedge acted as a duct measuring 6.5 in by 1/4 in to flow air from the supply line to the back of the helmet. Air then flowed up the back of the helmet, across the top of the helmet along the curvature of the helmet, down in front of the face, and out of the helmet through the neck area. The air inlet is different from the CFD version of the hemispherical open configuration helmet that has the air inlet located over the head instead of at the back of the helmet. Additionally, the CFD has a shorter, wider air inlet geometry; the hemispherical open helmet has a longer, narrower air inlet. Although the testing and the CFD results were similar, variances that occurred may be the result of differences in air mixing characteristics due to the air inlet locations.

Figure 9. Hemispherical open configuration helmets installed onto test stand.

The hemispherical conformal helmet configuration modifies the open configuration helmet by incorporating foam barriers to simulate the facial volume isolation that occurs with helmet occupant protection inserts. This configuration used a horseshoe-shaped foam insert to isolate the volume of air in front of the face, as well as an additional air duct to flow air from the back of the neck wedge, through the foam insert. See Fig. 10. The air flowed to the top of the helmet field-of-view, along the helmet bubble in front of the face, and out of the helmet through the front part of the neck area. A foam chin-piece insert was used to restrict air flow out of the helmet during some of the test runs; other runs were conducted without an insert. See Fig. 11.

Figure 10. Hemispherical conformal helmet installed onto test stand.

Conformal with Chin

Conformal Without Chin Piece

Figure 11. Hemispherical conformal helmet with and without foam chin insert.

The face dam conformal helmet is virtually identical to the model used for the CFD analysis. See Fig. 12. The analysis team actually modified the helmet from its original demand breathing configuration. The demand regulator at the back of the helmet was removed to enable the helmet to function as a continuous flow helmet, similar to the other helmet configurations.

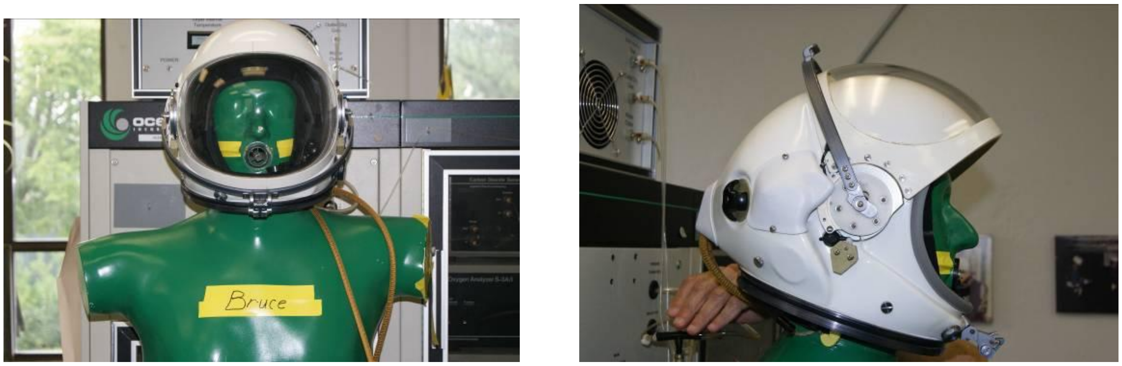


Figure 12: Face dam conformal helmet installed on test stand.

Hemispherical Open Configuration Helmet Testing

Testing of the hemispherical open configuration helmet showed CO_2 washout performance characteristics that the analysis team did not predict. Since this helmet by design does not conform to the head form, the positioning of the helmet was often inconsistent, which led to noticeable variations in CO_2 washout results. Additionally, the CO_2 washout performance at low-metabolic rate cases actually worsened when the air flow increased from 4.5 to 6.0 cfm. Although this helmet performed fairly well overall at 4.5 cfm, the real value of these test cases is an increased understanding of the performance characteristics.

During the first set of tests with clean air flowing (i.e., ambient air not contaminated with CO_2), the helmet performed well and with predictable results. CO_2 was injected into the air flow in the second set of tests. The improved performance results were not consistent with the team's expectations that performance would actually worsen. See Fig. 13 and Fig. 14. This led the analysis team to believe there may be problems with either the instrumentation or the helmet placement. After a recalibration ruled out instrumentation as the problem, the team looked at CO_2 washout performance with the helmet positioned in different ways.

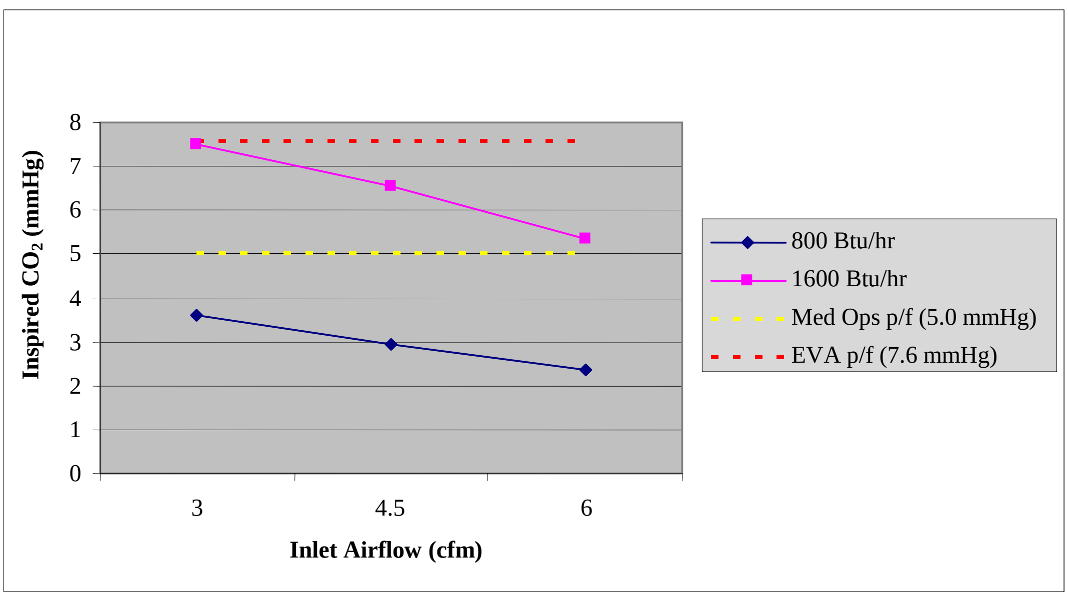
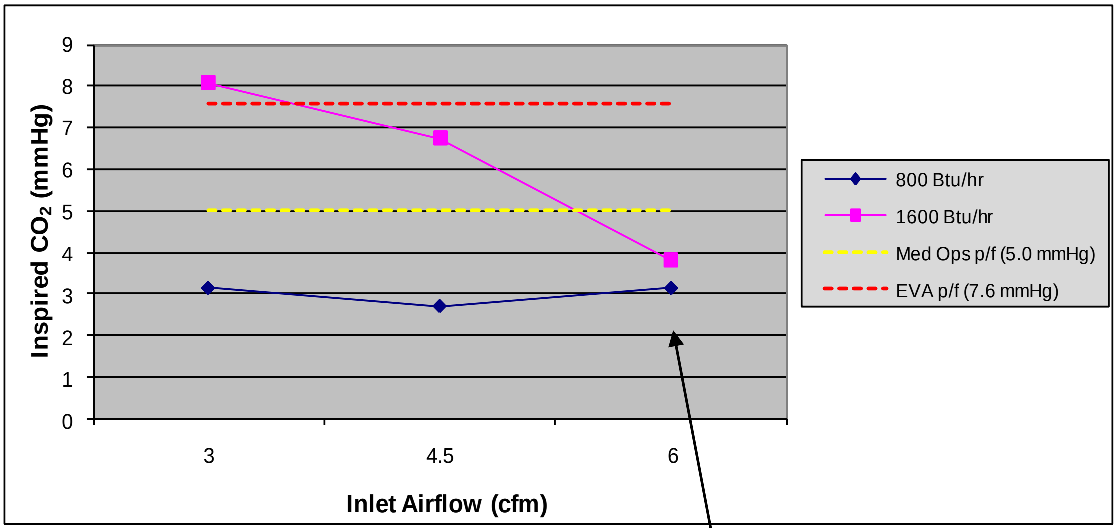


Figure 13. Day 1 – Hemispherical open helmet, no injected CO_2.



Note that inspired CO_2 increased as air flow increased for 800 Btu/hr.

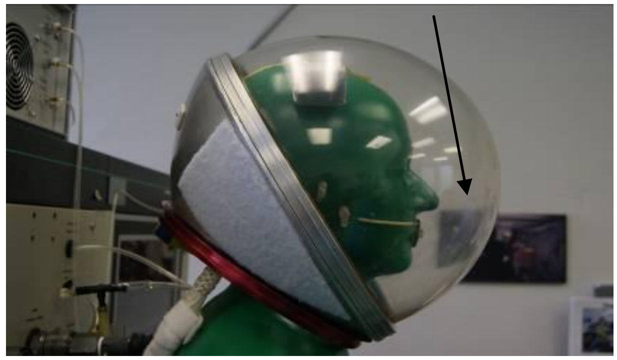
Figure 14. Day 1 – Hemispherical open helmet, 2.3 mmHg injected CO_2.

Rotating the helmet about 30 degrees to the left or right of the head form along the plane of the neck made the most significant impact in CO_2 washout performance. By rotating the helmet, the flow of air was no longer in front of the face. Rather, it offset the flow pattern causing the air to flow along the side of the face, away from the breathing area. Inspired CO_2 increased by as much as 7.3 mmHg when running a 3.0 cfm clean air case at 800 Btu/hr. Canting the helmet forward also increased the inspired CO_2 by as much as 2.3 mmHg. The helmet was also canted to the left and right of the head form, resulting in slight increases in inspired CO_2. See Fig. 15.

Before: Neutral Position

After: Helmet Rotated 30 Degrees

Note increased volume in front of face.



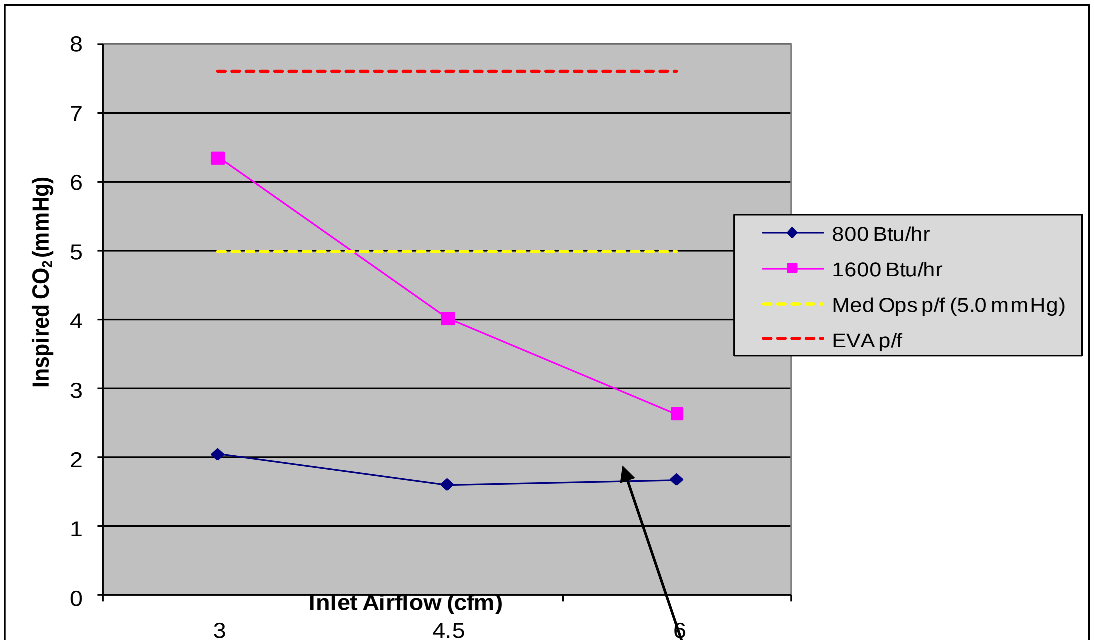
Before: Neutral Position

After: Helmet Canted Forward

Note the restricted air flow around front of neck ring.

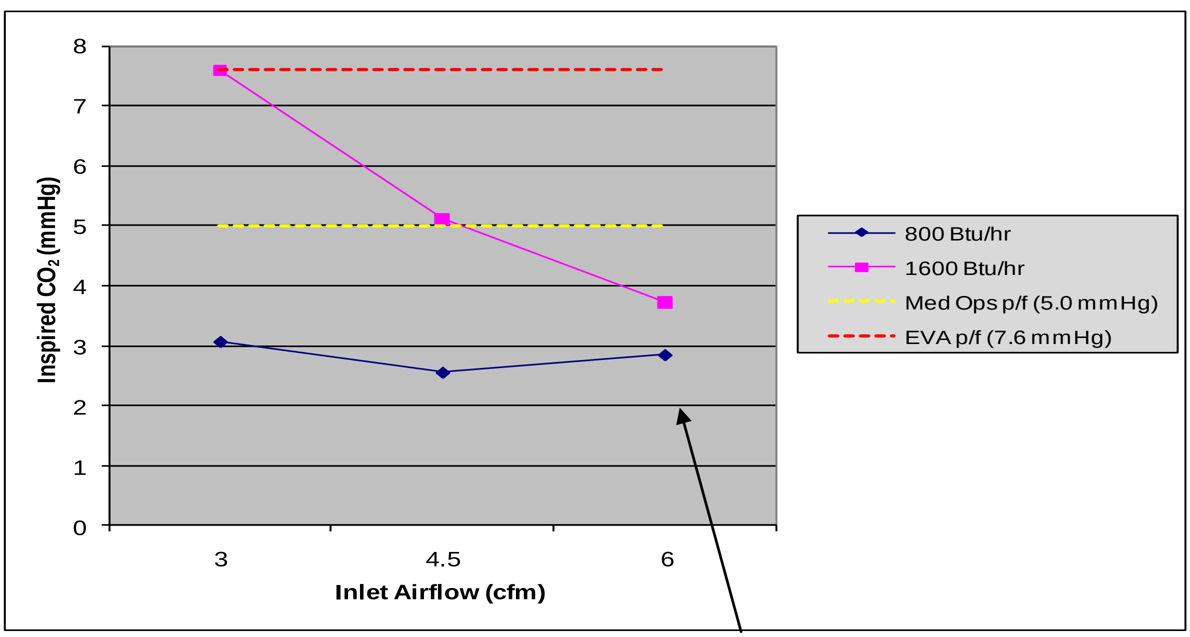
Figure 15. Hemispherical open helmet positions evaluated during troubleshooting.

The cases run with the repositioned helmet showed a high-level of sensitivity to the helmet placement onto the head form. Since the analysis team was not able to get a consistent placement, the data was not believed to be highly accurate. To further non-conformal helmet development, additional testing needs to be performed to characterize CO_2 washout with different head positions. However, the trends of the cases that were run before and after the troubleshooting effort were useful in showing that the high-metabolic cases improved the CO_2 washout as the air flow increased. Conversely, the low-metabolic cases did not necessarily improve as the air flow increased. See Fig. 16 and Fig. 17. The analysis team speculates that the latter scenario was a result of an air flow rate that was too high, which caused the CO_2 to mix in the helmet instead of blowing out of the breathing volume. Further testing is required in order to validate this speculation. When asked by EVA community if 6.0 cfm would be required or would it be optimal for CO_2 washout, these scenarios showed that more air flow is not necessarily better.



Note that inspired CO_2 increased as air flow increased for 800 Btu/hr.

Figure 16. Day 2 – Hemispherical open helmet, no injected CO_2.



Note that inspired CO_2 increased as air flow increased for 800 Btu/hr.

Figure 17. Day 2 – Hemispherical open helmet, 2.3 mmHg CO_2 injected.

Face Dam Conformal Helmet

The analysis team expected the face dam conformal helmet to perform the best out of all configurations because it has proven itself in regular military operations and because it performed well during the CFD analysis. However, although its performance was acceptable, it did not dramatically exceed the EVA success criterion as expected. At 4.5 acfm with clean air flowing in, the partial pressure of inspired CO_2 at the high-metabolic rate was just under the 7.6 mmHg EVA success criterion. For the low-metabolic case, the inspired CO_2 was well under the 5.0 mmHg success criterion required by the space medicine group. The team was unable to perform test cases with CO_2 injected into the helmet inlet line due to NIOSH hardware availability constraints. However, the team expected the helmet performance to degrade and fail based on the success criteria. See Fig. 18.

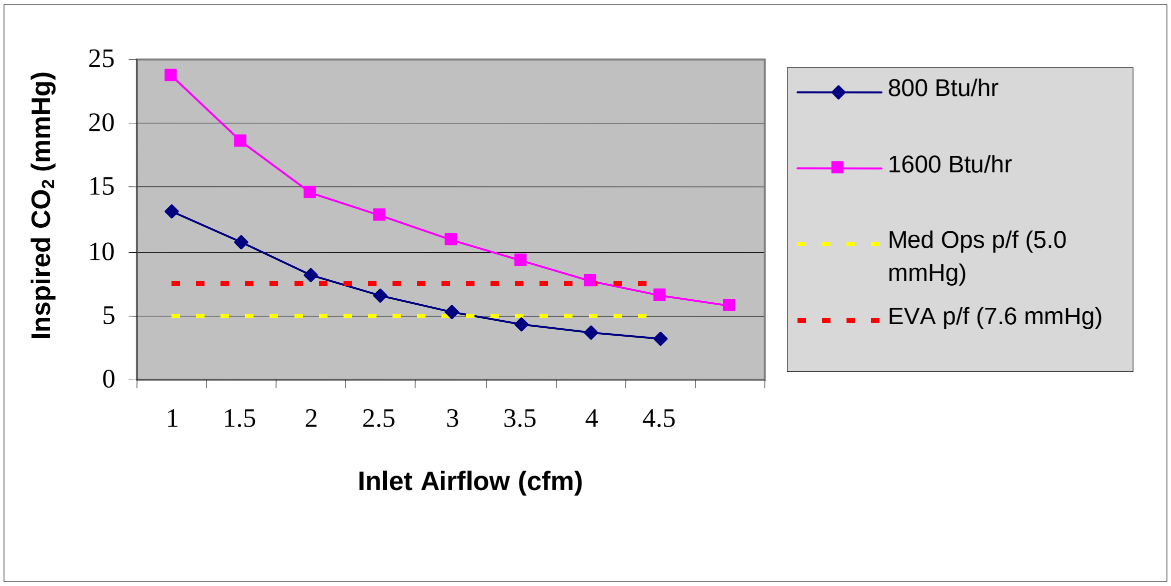


Figure 18. Face dam helmet, no inlet CO_2.

Because this helmet is a conformal helmet, the positioning of the helmet was consistent throughout all test runs. The helmet required a high-pressure inlet line from the air source that created enough pressure within the helmet breathing volume to make the helmet move up and down as the head form exhaled and inhaled. The amount of movement increased as the air flow increased, so testing ceased at 5.0 cfm to minimize the risk of damaging any hardware.

Hemispherical Conformal Helmet

This low-volume helmet concept performed about as well at NIOSH as the CFD model,. Most of the high-metabolic rate cases failed the EVA success criteria, with the exception of the 6.0 cfm, test point where no CO_2 was injected. This case measured an inspired partial pressure of just under 7.6 mmHg of CO_2. The low-metabolic rate cases performed better, yet all data points exceeded the Space Medicine success criteria of 5.0 mmHg. CO_2 washout performance did not change much when the chin piece was removed from the helmet. See Fig. 19 and Fig. 20.

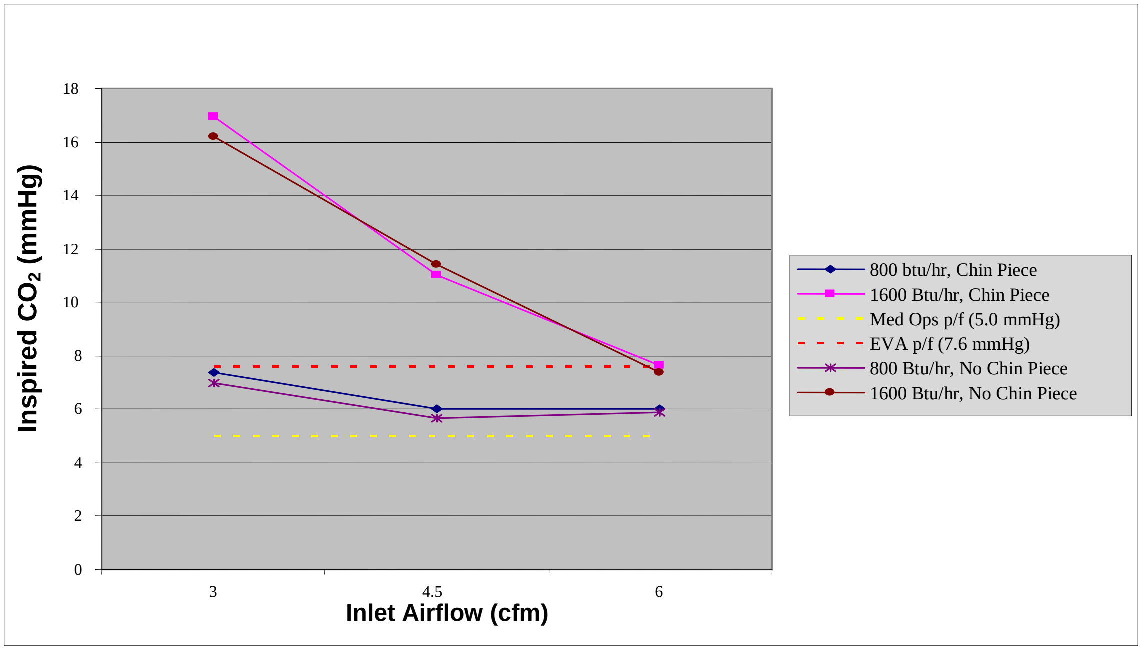


Figure 19. Results of Hemispherical conformal helmet, no injected CO_2.

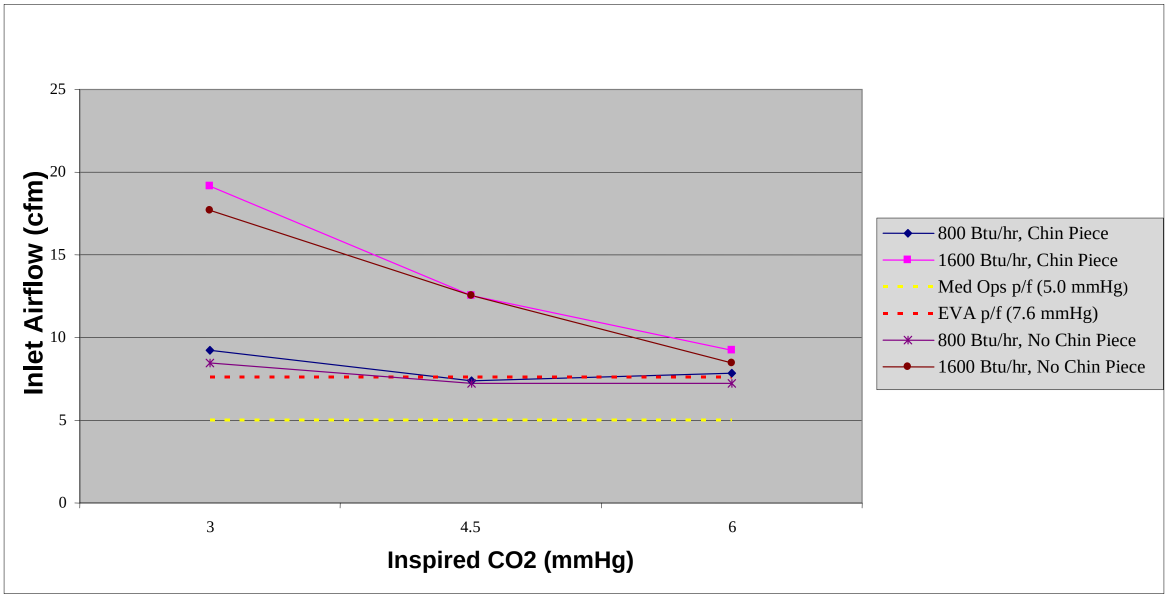


Figure 20. Results of Hemispherical conformal helmet, 2.3 mmHg CO_2 injected.

Alternative Configurations

After completing the scheduled tests, the team tested variations of the configurations previously detailed to characterize CO_2 washout performance with different helmet features. One set of runs used the open configuration helmet with the new air duct added to the helmet to evaluate air flow that starts above the face and terminates all around the neck area. See Fig. 21. Another configuration used the air duct and a neck dam made of foam with a cutout just below the chin to permit air flow. See Fig. 22. The idea behind this configuration was to create a channel of air around the oral-nasal area starting from the air inlet above the head and then terminating through the opening in the neck dam just below the face. The last configuration used only the new neck dam and air flowed from the neck wedge in a manner similar to the open configuration helmet to characterize airflow through the neck dam. See Fig. 23.

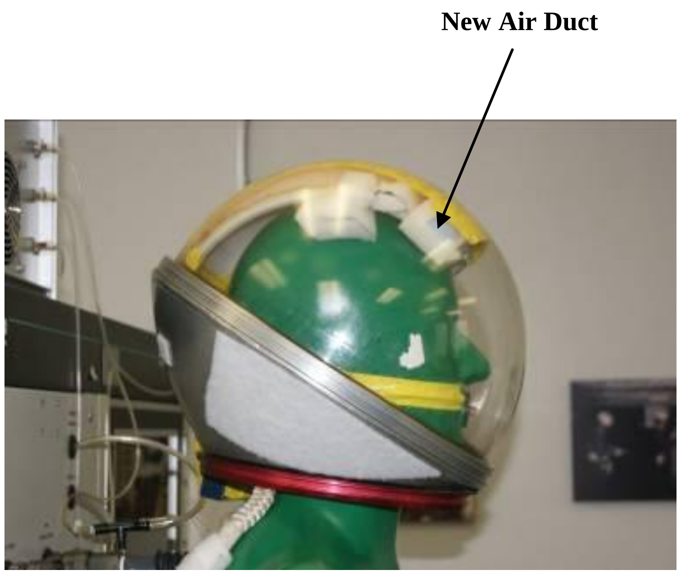


Figure 21. Hemispherical open helmet with new air duct.

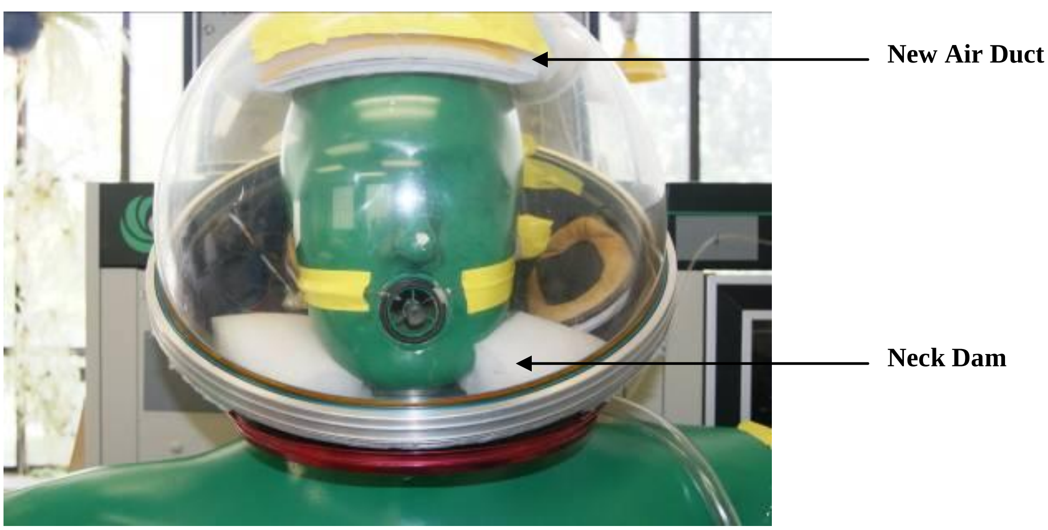


Figure 22. Hemispherical open helmet with new air duct and neck dam.

Figure 23. Hemispherical open with neck dam only.

Of the three alternate configurations, the helmet with the air duct and neck dam performed best. It met both success criteria at 4.5 acfm during the low-metabolic rate runs, the high-metabolic rate with clean air, and the high-metabolic rate with CO_2 injected into the air supply. See Fig. 24. A possible rationale for the superior performance is that this configuration flowed air as a continuous channel into the helmet, across the oral-nasal region, and out to the environment. Based on the CFD models, the other helmets tended to mix fresh air with expired CO_2 instead of efficiently washing it out of the helmet. Tests run with a fire rescue Gentex® helmet during a prior trip to the NIOSH may support this rationale. See Fig. 25.

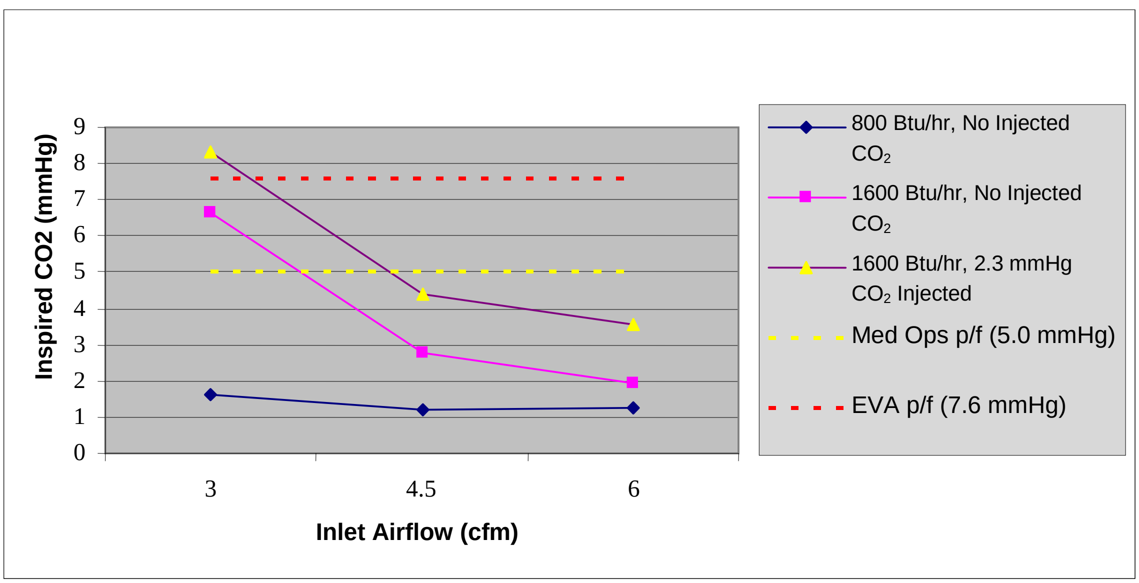


Figure 24. Hemispherical open helmet, neck dam, new air duct test results.

Figure 25. Gentex® test configuration.

The Gentex® helmet test runs yielded unexpectedly favorable results at 3.0 cfm and 1600 Btu/hr. Using an oral-nasal mask that allows air to blow side-to-side across the oral-nasal region, it successfully washed out CO_2 to an inspired partial pressure of around 5.8 mmHg, well within the EVA success criteria. The common element between the Gentex® and the new air duct/neck dam configuration appears to be the channeled flow concept through a narrow outlet, whether it was top-to-bottom or side-to-side. The hemispherical conformal helmet also used a channeled flow concept, but the smaller volume may have allowed for more mixing of exhaled CO_2 with fresh air instead of removal of CO_2. From a helmet development standpoint, this channeled-flow concept deserves further investigation as part of a design solution to improve CO_2 washout.

The other alternate configurations -- air duct only and then later the neck dam only -- also performed well, with all results remaining under the EVA success criteria of 7.6 mmHg. Both configurations used the channeled air flow idea to a lesser extent than the duct/dam configuration, but the open-neck outlet without the neck dam did not perform as well as the neck dam configuration. Enough channeling flow may have minimized the mixing of fresh air with CO_2 to provide improved CO_2 washout. See Fig. 26 and Fig. 27.

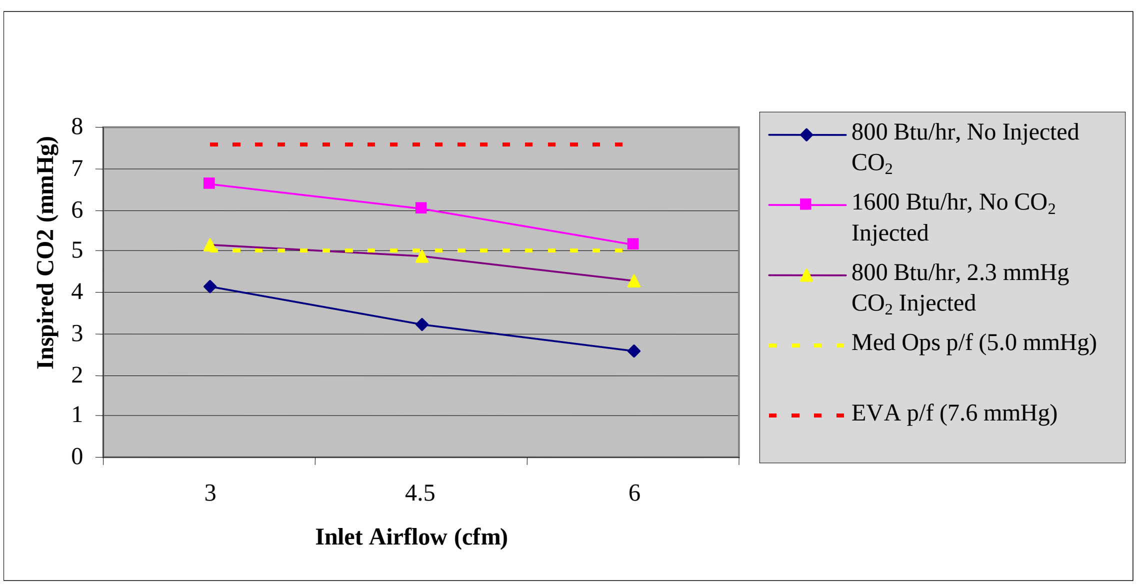


Figure 26. Hemispherical open helmet, neck dam.

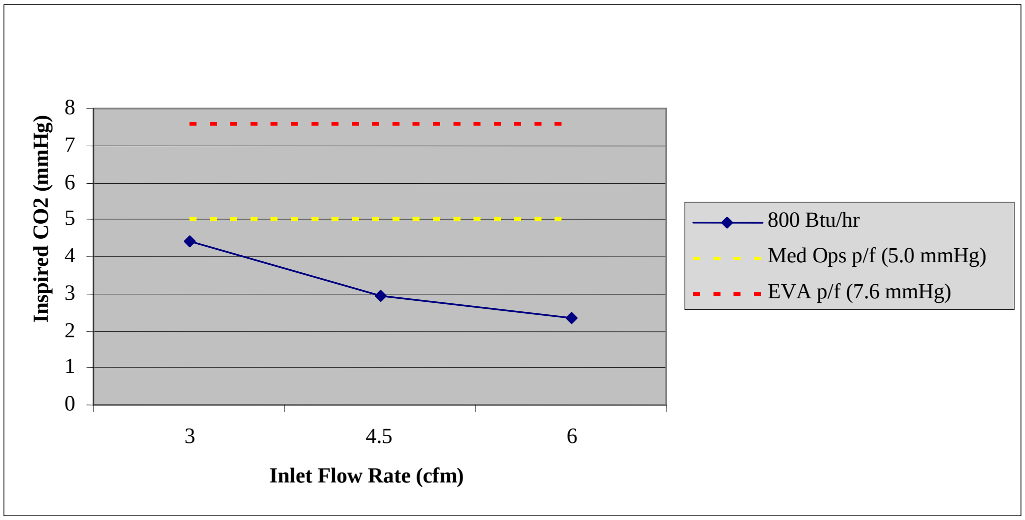


Figure 27. Hemispherical open helmet, new air duct.

V. Conclusion

The CO_2 washout analysis provided several data points that characterize CO_2 washout within space suit helmets. Both the testing at NIOSH and the CFD modeling showed washout performance trends that were generally consistent with each other. Some helmet configurations performed better than others, but none of the CxP helmet concepts were able to satisfy all the success criteria, particularly the high metabolic rate cases. It was clear that proper detailed design of the helmet geometry and its ventilation paths is crucial to achieve proper washout. Several cases successfully washed out CO_2 at 4.5 acfm and this gave the analysis team enough confidence to recommend this air flow value. However, the definition of a success criterion for proper washout could not be agreed upon during the analysis. Given this disparity, the analysis team did not have a compelling rationale to accept air flow of less than 4.5 acfm. Additionally, the low-metabolic cases that experienced diminished CO_2 washout performance when the air flow increased from 4.5 to 6.0 acfm could not be explained. Thus, the analysis team concludes that 4.5 acfm of air flow from the suit loop can adequately washout CO_2.

References

[1]"Constellation Integrated Risk Management Application (IRMA), risk no. 4025, Insufficient Breathing Gas Flow from Orion," JSC, Houston: NASA, 10 February 2009.

[2]"CxP 70024, Constellation Program Human-Systems Integration Requirements," Rev. C. JSC, Houston: NASA, 06 March 2009.

[3]Paul, Heather L., Waguespack, Glenn. Conger, Bruce, Paul, Thomas H., "Helmet Exhalation Capture System (HECS) Sizing Evaluation for an Advanced Space Suit Portable Life Support System," International Conference on Environmental Systems, SAE Paper No. 2008-01-2117, June 2008.

[4]Gilbert, John and Schentrup Susan, "Determination of Residual Carbon Dioxide During Forced Ventilation of a Hemispherical Space Suit Helmet - Final Test Report," 31 January 1991.